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Failure Model for a Leaking Nickel-Hydrogen Cell

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14. ABSTRACT

A model has been developed and used to analyze the loss of capacity and dry out of nickel-hydrogen cells as a result of pressure vessel leaks. This analysis has allowed a number of conclusions to be drawn about the behavior of nickel-hydrogen cells with leaks:

- Cells that are repeatedly cycled may not lose all capacity by leaking their hydrogen.
- There is a leak size threshold at 1–2.5 μm below which nickel-hydrogen cells will not dry out by gas.
- There is a leak size threshold at 0.1–0.2 μm below which it will be difficult to identify the rate of capacity loss as differing significantly from normal wear-related capacity loss rates.
- Pre-existing leaks smaller than about 0.1 μm cannot be detected by typical leak detection methods.
- Leak latency can occur if pre-existing subthreshold leaks grow in size during the cell operation.

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1. Introduction

Nickel-hydrogen cells operate using hydrogen gas as the active material for energy storage in the negative (hydrogen) electrode of the cell, and nickel hydroxide as the active material for energy storage in the positive (nickel) electrode. Cell operation therefore requires a pressure vessel to contain the hydrogen gas needed for charge and discharge of the cell capacity at the negative electrode. Nickel-hydrogen cells typically operate in an inconel pressure vessel at pressures of up to about 1000 psi of hydrogen gas.

If the nickel-hydrogen cell pressure vessel develops a leak during operation, the hydrogen gas will be lost from the cell. In this situation, a cell is normally regarded as being failed since its standard capacity can drop to nearly zero. However, a cell in this state has not completely lost the capability to pass current or all its capacity until it develops high internal impedance due to cell dry out. The reason for this is that more hydrogen gas can be generated within the cell as a result of electrolysis reactions involving the water in the electrolyte. In addition, until a cell develops high impedance, it does not necessarily cause the complete failure of a battery containing that cell in a series connection with other cells. Particularly, if cell bypass diodes are used in the battery, the battery will continue to function at a voltage that is reduced by the voltage of the cell that has leaked. If there are no bypass diodes. the battery will only fail when the leaking cell develops high internal impedance due to electrolyte dry out.

In this report, we have modeled the rate at which gases can escape from a nickel-hydrogen cell through small leaks of various sizes, and have determined the expected effects of leaks on cell performance. In this model, we take into account the electrochemical processes within the cell and the physics of gas leaks. The purpose of this study is to determine whether there is a leak size threshold below which a cell would not completely fail by capacity loss, and whether there is another somewhat larger leak size threshold below which a nickel-hydrogen cell would not be expected to fail due to a high-impedance condition.

2. Modeling Method

2.1 Cell Performance Model

The cell performance model used here follows the behavior of a cell during continuous cycling and allows the cell capacity, C, initial percentage of nickel precharge, C_{oNi}, the percent depth of discharge ,D_{OD}, recharge ratio, R_R, the total cycle time, t_c, and the discharge time ,t_d, to be varied as desired. In addition, the model requires the total weight of electrolyte, W_t, in the cell and the initial weight percent, W_{op}, to be specified. The model starts assuming that the cell is charged to 100% state of charge (SOC) at its maximum expected operating pressure (MEOP), P_{MEOP}, and that there has been no pressure vessel leak up to the starting point. The discharge current during each cycle is computed from Eq. (1) and provides the specified DOD for each cycle. The recharge current is based on Eq. (2), and assumes 100% charge efficiency until the nickel electrode is 100% charged, and 0% charge efficiency thereafter.

$$I_d = C\frac{0.01D_{OD}}{t_d} \tag{1}$$

$$I_c = C\frac{0.01D_{OD}R_R}{t_t - t_d} \tag{2}$$

The state of charge of the nickel electrode S_{Ni} is assumed to change according to the ampere-hours discharged or recharged, but is limited to 100% during recharge and cannot go below 0% during discharge. The percent nickel precharge at any time, C_{Ni}, is obtained from Eq. (3), but does not change from the initial precharge level, C_{oNi}, unless the cell leaks some hydrogen or oxygen gas.

$$C_{Ni} = S_{Ni} - 100(P_{H_2} - 2P_{O_2})\frac{1 - 0.01C_{oNi}}{P_{MEOP}} \tag{3}$$

The hydrogen pressure P_{H2} and the oxygen pressure P_{O2} within the cell are assumed to change during charge and discharge according to the following rules:

a. *Hydrogen gas changes in the cell*

1. Hydrogen is produced with 100% efficiency at the negative electrode during recharge if the nickel electrode state of charge is less than 100% and no oxygen gas is present, and 0% efficiency if the nickel electrode is at 100% state of charge.

2. Hydrogen gas is consumed with 100% efficiency at the negative electrode during discharge as long as any hydrogen is present.

3. Hydrogen gas is produced at the positive electrode with 100% efficiency during discharge if the state of charge of the nickel electrode falls to 0% (reversal).

4. Hydrogen may be lost through a leak path.

b. Oxygen gas changes in the cell

1. Oxygen from overcharge at the nickel electrode (Ni SOC = 100%) is assumed to recombine with and cancel out hydrogen generated at the negative electrode during overcharge.

2. Oxygen gas is produced with 100% efficiency during discharge at the negative cell electrode if the hydrogen pressure is depleted.

3. Oxygen gas is consumed with 100% efficiency during recharge at the negative cell electrode until the oxygen pressure is depleted.

4. Oxygen may be lost through a leak path.

2.2 Cell Leak Model

The leak rate of gas through a hole in the pressure vessel of a nickel-hydrogen cell is modeled using the Poiseuille equation for gas flow through a tube of length L and radius r, when the gas pressure on the inside of the tube is P and the pressure at the exterior opening of the tube is zero. Eq. (4) gives the flow rate of gas through the tube in cm^3/s.

$$\frac{dV}{dt} = \frac{\pi r^4 P}{16 L \eta} \tag{4}$$

The viscosity of the escaping gas is expressed by η in Eq. (4). Since, in general, the escaping gas can be a mixture of hydrogen and oxygen, the viscosity of the escaping gas is given by Eq. (5)

$$\eta = \eta_{H_2} \frac{P_{H_2}}{P_{H_2} + P_{O_2}} + \eta_{O_2} \frac{P_{O_2}}{P_{H_2} + P_{O_2}}, \tag{5}$$

where the viscosity of hydrogen in poise is given by Eq. (6)

$$\eta_{H_2} = 88.73 \times 10^{-6} \sqrt{\frac{T}{293}}, \tag{6}$$

and the viscosity of oxygen in poise is given by Eq. (7), where T is the absolute temperature.

$$\eta_{O_2} = 203.31 \times 10^{-6} \sqrt{\frac{T}{293}} \tag{7}$$

The total volume of gas flowing through the tube in a given time increment is partitioned into a volume of hydrogen and a volume of oxygen according to the relative pressure of each gas within the cell. The moles of hydrogen and oxygen lost from the cell are obtained from the gas volumes assuming ideal gas behavior, and the pressures of oxygen and hydrogen are adjusted for the change in the moles of each gas within the cell.

The loss of hydrogen or oxygen from a nickel-hydrogen cell through a leak will affect the cell capacity and the precharge in the cell by changing the amount of hydrogen in the charged cell. The capacity loss can affect the cell energy storage capability relatively rapidly. However, the cell will still have low impedance, and can generate oxygen or hydrogen gases during charge or discharge. Complete cell (and possibly battery) failure will occur when the cell is driven to a high impedance condition by loss of the water needed in the electrolyte for conductivity. Here we assume that the cell will develop high impedance that will prevent all current flow when the concentration of the KOH electrolyte reaches 51%, which is where the KOH electrolyte will solidify.

The changes in electrolyte concentration are modeled by changing the amount of water within the cell to reflect the losses of electrolytically generated hydrogen and oxygen through the leak. Eq. (8) shows this relationship.

$$W_p = 100 \frac{W_{KOH}}{W_{KOH} + W_{water}}, \tag{8}$$

where W_{KOH} is the weight of KOH in the cell electrolyte, and W_{water} is the weight of water in the electrolyte. Eq. (9) gives the weight of KOH in the electrolyte, which is assumed to remain invariant through cycling in this model, and Eq. (10) gives the weight of water remaining in the electrolyte.

$$W_{KOH} = 0.01 W_{op} W_t \tag{9}$$

$$W_{water} = W_t - W_{KOH} - 18 M_{H_2} - 36 M_{O_2} \tag{10}$$

In Eq. (10), M_{H2} is the cumulative moles of hydrogen gas lost from the cell through the leak, and M_{O2} is the cumulative moles of oxygen gas lost.

3. Modeling Results

As indicated by Eq. (4), the impact of a leak on the performance of a nickel-hydrogen cell is expected to be most strongly dependent on the radius of the leak path since the leak rate depends on r^4. However, there is an additional dependence on the length of the leak path. To evaluate the role of the leak radius, we have initially run the model for a range of radii using a leak path length of 100 μm (about 4 mils), which is 10–20% of the typical pressure vessel wall thickness for nickel-hydrogen cells. The model was run for a 15% DOD cycle, with 90 min for the cycle time and 30 min for the discharge time. The nickel precharge was initially 15% and the MEOP for the cell was 900 psi. The cell was filled with 3.4 g/Ah of 31% KOH electrolyte. Figure 1 indicates the pressures of oxygen and hydrogen within this cell during 500 cycles with a leak having a 2-μm radius.

As indicated in Figure 1, the hydrogen is lost quite rapidly from the cell through the leak. After only about 50 cycles, the amount of hydrogen within the cell has dropped to a level where the cell has insufficient remaining capacity to support the 15% DOD at which it is cycling, resulting in the reversal of the cell and the generation of some oxygen. However, Figure 1 also shows that the cell still has some hydrogen capacity (approximately 40 psi) after 500 cycles. In fact, since both hydrogen and oxygen are generated from the water in the electrolyte during each cycle, the cell will always have some hydrogen to support discharge at the end of each recharge period, although the amount can be relatively small. Hydrogen gas tends to leak from the cell much more readily than does oxygen gas because it is produced at twice the pressure as oxygen (for a given Ah throughput), and because the viscosity of hydrogen is considerably lower than that of oxygen gas.

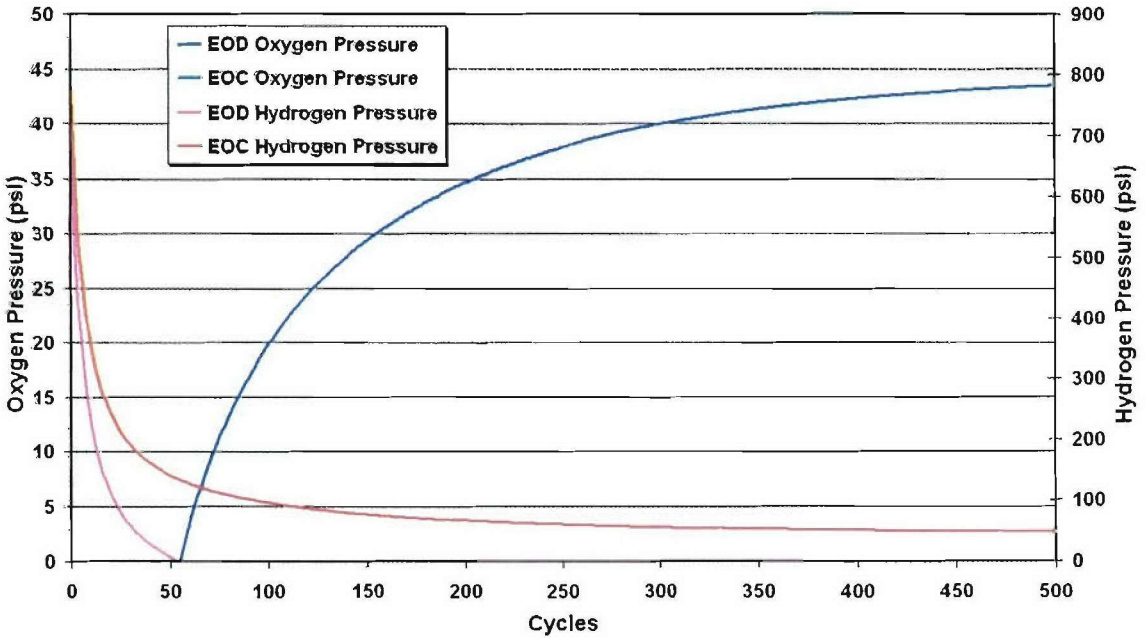

Figure 1. Hydrogen and oxygen pressures in a nickel-hydrogen cell with a leak (r = 2 μm, L = 100 μm) during cycling at 15% DOD for 35 days.

Figure 2 shows the changes in nickel precharge in the cell and the changes in electrolyte concentration during the same 500 cycles indicated in Figure 1. As the cell leaks hydrogen gas, the level of nickel precharge rises towards 100%. However, it never reaches 100% because the loss of oxygen (which reduces the Ni precharge) will eventually balance the loss of hydrogen during each cycle. When this balance condition is reached, the only change in cell behavior from cycle to cycle is a slow increase in electrolyte concentration resulting from loss of water to the electrolysis processes that continually restore the leaking hydrogen and oxygen. The increase in electrolyte concentration, which is shown in Figure 2, is expected to cause a gradual increase in cell resistance, which will eventually result in an open (high-impedance) condition when the electrolyte crystallizes at a concentration of about 51%.

Because of the r^4 dependence of the gas flow rate on the radius of a leak (from the Poiseuille Equation), the response of a cell to a leak is highly dependent on the size of the leak. This dependence is illustrated in Figure 3, where the time (in years) until the electrolyte concentration rises to 51% as a result of leaking gases, is plotted as a function of leak radius for differing leak path lengths. The data plotted in Figure 3 are also provided in Table 1, where days to failure are indicated.

The results in Figure 3 and in Table 1 show that there is clearly a threshold of leak radius below which a nickel-hydrogen cell will not fail in a high impedance condition in a time frame of ten years or less. This threshold occurs for leak radii less than 1 to 2.5 μm, depending on the length of the leak path. While cells with leaks of this approximate size will appear to rapidly lose much of their capacity as a result of loss of hydrogen gas, they will not lose all their capacity for up to ten years, and they will not fail by developing a high impedance from cell dry out. This behavior results because the relatively small amount of hydrogen in a cell can escape rapidly from the high-pressure cell environment, but the large amount of water in the electrolyte must gradually be electrolyzed to hydrogen and oxygen before it can escape from the low-pressure cell environment.

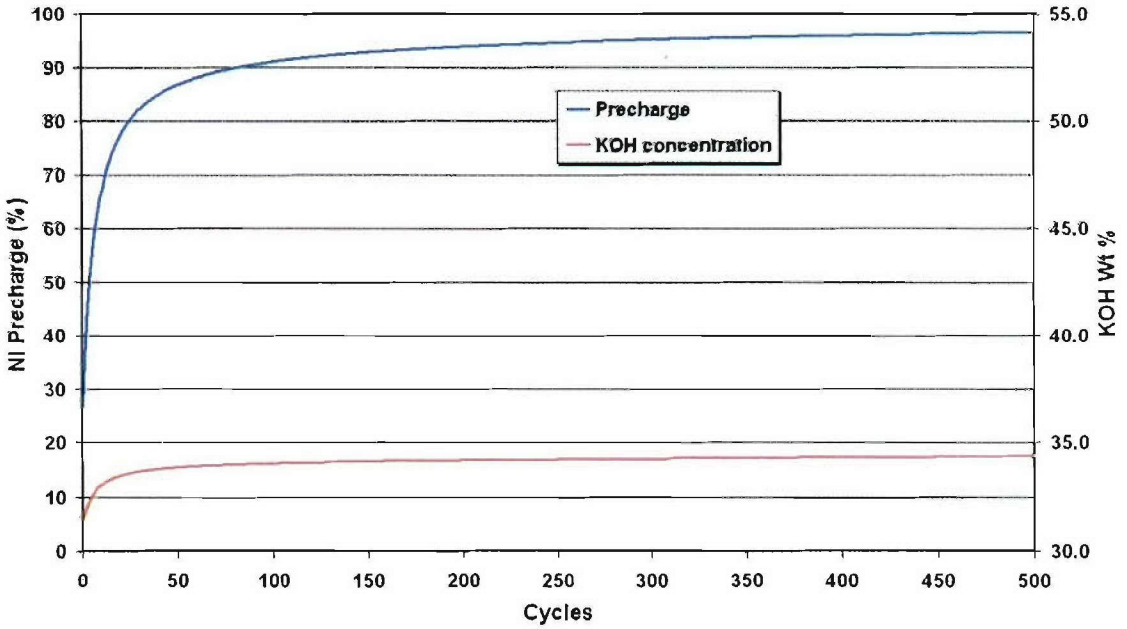

Figure 2. Level of nickel precharge and KOH concentration in a nickel-hydrogen cell with a leak (r = 2 μm, L = 100 μm) during cycling at 15% DOD for 35 days.

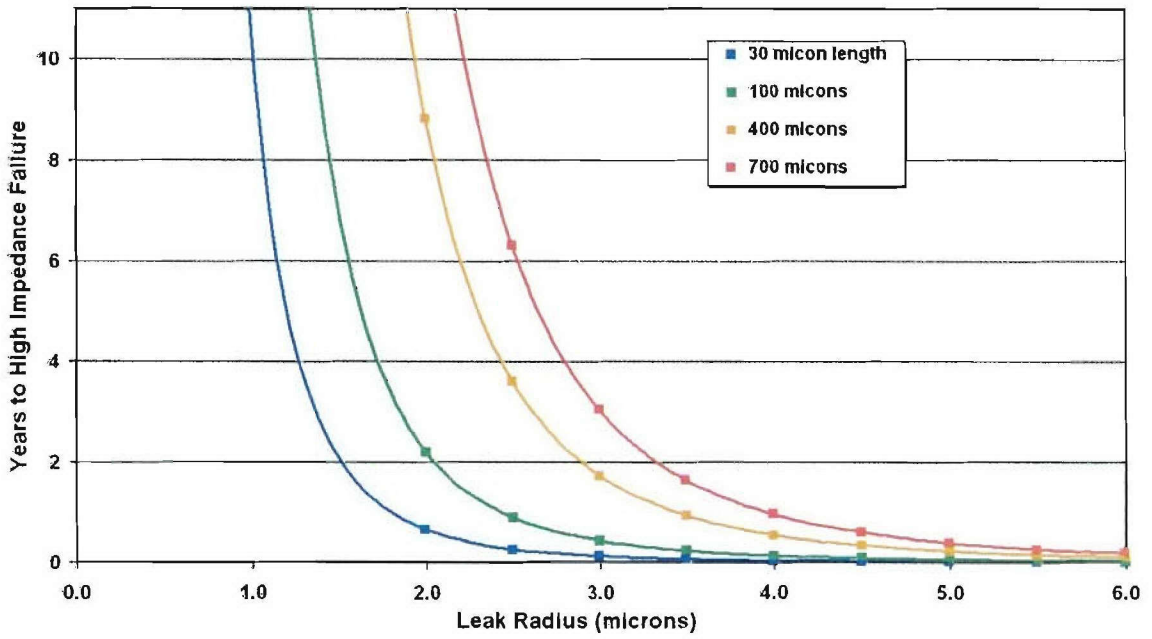

Figure 3. Years to a high impedance cell failure as a function of leak size, assuming 15% DOD cycling at 10°C.

Table 1. Constants Defining Years to Cell Failure in Eq. (11), and the Days to Cell Failure for Various Leak Lengths and Radii in Micrometers

	Leak length			
Constants	**30 μm**	**100 μm**	**400 μm**	**700 μm**
A	**10.5871**	**35.291**	**141.4537**	**246.8913**
B	**–4.0002**	**–4.0001**	**–4.0014**	**–3.9996**
Leak radius	**Days to Failure**			
2.0	241.48	805.02	3223.78	5633.77
2.5	98.91	329.73	1320.05	2307.80
3.0	47.70	159.01	636.44	1113.02
3.5	25.74	85.83	343.46	600.82
4.0	15.09	50.31	201.29	352.21
4.5	9.42	31.41	125.64	219.89
5.0	6.18	20.61	82.42	144.28
5.5	4.22	14.07	56.29	98.55
6.0	2.98	9.94	39.74	69.58
6.5	2.16	7.21	28.85	50.52
7.0	1.61	5.36	21.45	37.56
7.5	1.22	4.07	16.27	28.50
8.0	0.94	3.14	12.57	22.02

The results in Figure 3 and in Table 1 also show that cell failure from high impedance can occur on a time scale of weeks or less if a leak having a radius greater than about 5 μm is present. These results

indicate that risk factors for leaks in nickel-hydrogen cells should be avoided to prevent open-circuited cells simply because it cannot be assured that all leaks will be less than about 5 μm in radius. It is clear that only days or weeks are needed to produce failure for larger leaks, while small leaks may take many years to cause cell failure as a result of high impedance. The time to a high impedance failure in years F_{yr}, was found to be related to leak radius by a power law for each leak length, as indicated by Eq. (11).

$$F_{yr} = Ar^{B} \tag{11}$$

The constants A and B in Eq. (11) are provided in Table 1. The constant B was found to be essentially –4.0, as expected from Eq. (4).

The results described above suggest that there should also be a leak threshold below which a nickel-hydrogen cell will not lose more than about 10% of its capacity over 10 years of operation. If we use the model described here to determine this threshold, the results indicated in Figure 4 and Table 2 are obtained. These results indicate that if a leak is less than about 0.1 to 0.2 μm in radius, the cell will not lose more than about 10% of its capacity in a 10-year operating lifetime. This threshold can vary somewhat in this range depending on the length of the leak. This same analysis, however, also indicates that a cell having a leak with a radius greater than about 0.4 μm will rapidly lose most of its hydrogen gas (and capacity) as a result of the leak.

The lower threshold for a detectable leak suggested by the results in also suggest that a leak could exist that is largely plugged with solid KOH, carbonates from the cell, or other residue, and that this plug could hold hydrogen gas until it is dissolved by exposure to aqueous solution or otherwise

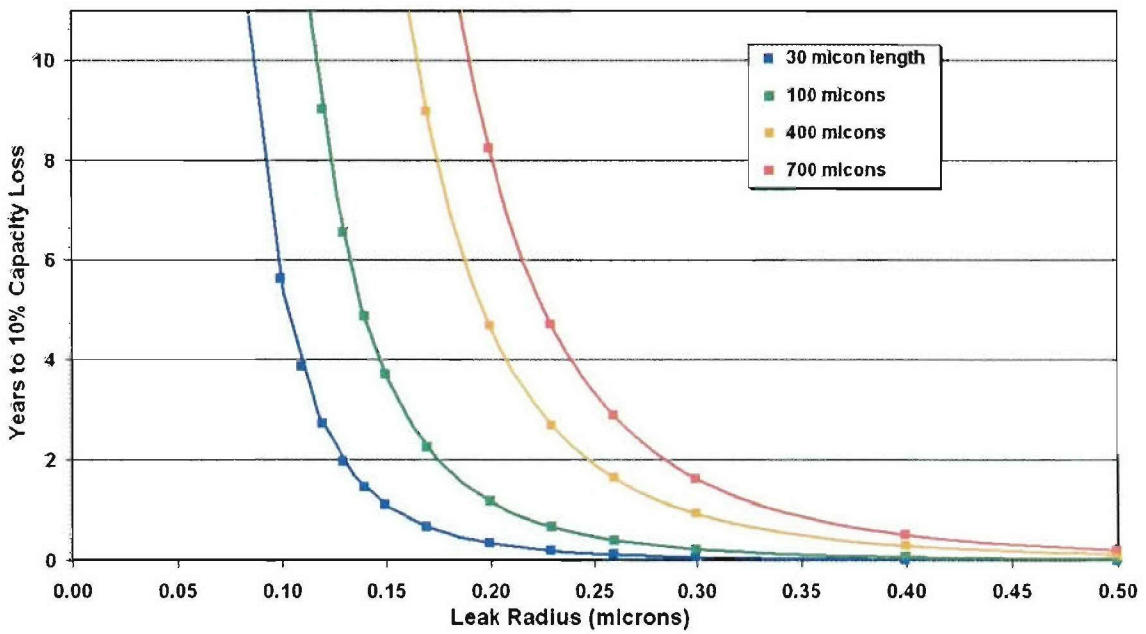

Figure 4. Years until 10% of cell capacity has been lost due to hydrogen leaking as a function of leak size, assuming 15% DOD cycling at 10°C.

Table 2. Constants Defining Years Until 10% of Cell Capacity Has Been Lost Due to a Hydrogen Leak Based on Eq. (11), and the Years to 10% Capacity Loss for Various Leak Lengths and Radii in Micrometers

	Leak length			
Constants	**30 μm**	**100 μm**	**400 μm**	**700 μm**
A	**0.000563**	**0.00188**	**0.00751**	**0.01321**
B	**–3.9997**	**–3.9975**	**–4.0000**	**–4.0001**
Leak radius	**Days to 10% capacity loss**			
0.10	2054.6617	6837.4917	27397.9950	48213.0002
0.11	1403.4017	4671.2118	18713.1992	32929.8140
0.12	990.9211	3298.9048	13212.7677	23250.4442
0.13	719.4508	2395.5667	9592.7996	16880.2686
0.14	534.8993	1781.3530	7131.9229	12549.8173
0.15	405.9085	1351.9854	5411.9496	9523.1695
0.17	246.0446	819.7421	3280.3720	5772.2539
0.20	128.4431	428.0844	1712.3747	3013.1037
0.23	73.4408	244.8442	979.0558	1722.7277
0.26	44.9750	149.9826	599.5500	1054.9437
0.30	25.3746	84.6456	338.2469	595.1568
0.40	8.0294	26.8017	107.0234	188.3059
0.50	3.2890	10.9841	43.8368	77.1284

dislodged. The only requirement for this to occur would be that any crevices through the plug would have to initially be smaller than 0.1 μm in radius, which would render them virtually undetectable.

As an example, a leak that resulted in 10% capacity loss in one day would have a relatively sizeable radius of 0.68 μm (assuming a 30-μm length). If this leak involved a crack 0.3 μm wide, the crack would have to be 4.8 μm long to have the same cross-sectional area as the tubular leak.

The hydrogen leak rate that can result in loss of 10% of the cell capacity in a ten-year period is about 2.0×10^{-7} cm^3/s at the cell operating pressure (900 psi), a leak rate that will be exceeded for any tubular leak larger than 0.1 to 0.2 μm. This is equivalent to a leak rate at 1 atm of 1.23×10^{-5} std cm^3/s. The leak rates that were obtained for various leak radii and lengths are indicated in Figure 5 and Table 3. The leak rate in Table 3 follows the form of Eq. (11) with an exponent of 4.0, as dictated by the Poiseuille equation, Eq. (4). The small deviations in Table 3 from 4.0 for the constant B result from round-off errors in the computations and curve fitting procedures.

Figure 5 also indicates the maximum leak rate at 1 atm allowed by leak checks in most cell manufacturing specifications, which is 1.6×10^{-6} std cm^3/s. For most leak test methods, the sensitivity of the leak check method is typically an order of magnitude less than this maximum, and is about 1.0×10^{-7} std cm^3/s. Table 3 shows that with this sensitivity level, any leak having a radius less than about 0.1 μm will not be detected during the initial leak tests done on a cell when it is new. Whether this is a potential problem for long-term cell performance depends on whether such a leak is stable in size. If it is stable, the resulting loss of hydrogen gas will only result in about a 1% capacity loss over 10

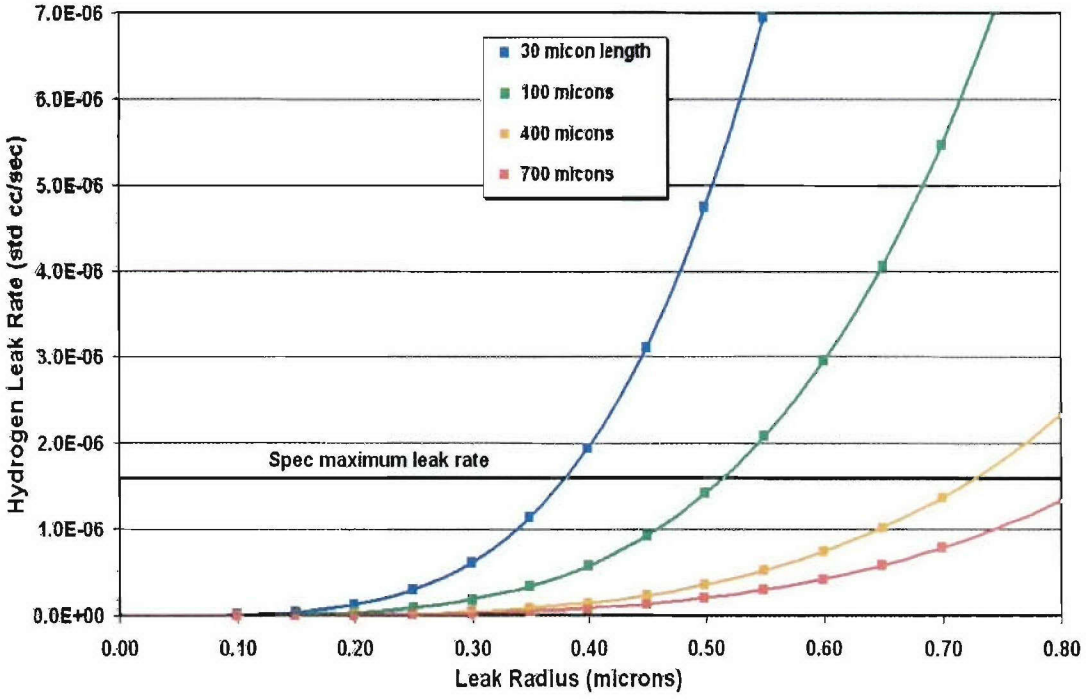

Figure 5. Rate of hydrogen leakage from a nickel-hydrogen cell at 900 psi as a function of leak size, assuming 15% DOD cycling at 10°C.

Table 3. Constants Defining the Hydrogen Leak Rate in Standard cm^3/s (at a pressure of 1 atm) Based on Eq. (11), and the Hydrogen Leak Rate for Various Leak Lengths and Radii in Micrometers

	Leak length			
Constants	**30 μm**	**100 μm**	**400 μm**	**700 μm**
A ($x10^6$)	**75.9712333**	**22.7997000**	**5.6960867**	**3.2568667**
B	**4.0001**	**4.0004**	**4.0000**	**4.0004**
Leak radius	**Standard Leak rate (std cm^3/s)**			
0.10	7.595E-09	2.278E-09	5.696E-10	3.254E-10
0.15	3.845E-08	1.153E-08	2.884E-09	1.648E-09
0.20	1.215E-07	3.646E-08	9.114E-09	5.208E-09
0.25	2.967E-07	8.901E-08	2.225E-08	1.272E-08
0.30	6.153E-07	1.846E-07	4.614E-08	2.637E-08
0.35	1.140E-06	3.420E-07	8.548E-08	4.885E-08
0.40	1.945E-06	5.835E-07	1.458E-07	8.335E-08
0.45	3.115E-06	9.346E-07	2.336E-07	1.335E-07
0.50	4.748E-06	1.425E-06	3.560E-07	2.035E-07
0.55	6.951E-06	2.086E-06	5.212E-07	2.980E-07
0.60	9.845E-06	2.954E-06	7.382E-07	4.220E-07
0.65	1.356E-05	4.069E-06	1.017E-06	5.813E-07
0.70	1.824E-05	5.473E-06	1.368E-06	7.819E-07

years due to hydrogen loss. However, if the leak grows in size as a result of pressure cycling, it would only have to grow to about 0.2 μm in effective radius before relatively rapid cell capacity loss would be observed.

4. Discussion

A number of interesting observations have emerged from this analysis of how a nickel-hydrogen cell is expected to respond to a leak in its pressure vessel. The first observation is that there is a size threshold for a leak below which the leak cannot be detected by normal leak check procedures when a cell is manufactured because the leak rate is below the detection limit of the detectors. This threshold is approximately 0.1 μm. If a leak of this magnitude is present, and does not grow over the operational life of the cell, it will not result in noticeable capacity loss. However, if this type of pre-existing leak does increase in size to about 0.2 μm or more as a result of pressure cycling or other aspects of cell operation, it will cause relatively rapid cell capacity loss as a result of hydrogen leaking.

Another interesting result is that a cell that has a hydrogen leak will not lose all its capacity if it is continuously cycled. Before all capacity is lost, the leaking of oxygen generated during reversal and recharge will balance the leaking of hydrogen during the latter stage of the recharge period. The amount of capacity that will remain depends on the relative loss of hydrogen and oxygen during the overall cycle. Balance occurs when the ratio of hydrogen to oxygen lost through the leak is 2.0, which will just result in the loss of the amount of water from the electrolyte that is needed to electrolytically produce these gases. Thus, the observation of capacity loss from a nickel-hydrogen cell, which is followed by a stabilization of the capacity at a lower level, does not necessarily mean that a leak has occurred and has subsequently resealed after the pressure dropped to a lower level. This is the typical interpretation of nickel-hydrogen cell behavior. A more correct interpretation would include the possibility of balancing hydrogen losses against oxygen losses, with the net result being the long-term dry out of the cell (which can take many years).

After a cell is cycling, there is a threshold of leak size below which capacity losses are so slow that they probably would not be attributed to a leak. This leak size threshold is 0.1 to 0.2 μm, which is similar to the minimum leak size that can be typically detected by cell manufacturers when a cell is first built. If a leak is much greater than 0.2 μm in radius, it can be detected readily as a loss of cell capacity or pressure, assuming that capacity checks are performed, or that the cell capacity falls below the SOC needed to support discharge.

If a cell continues to leak hydrogen and oxygen gas over a long period of operation, it will eventually lose enough water that the electrolyte will dry out and the cell will fail by developing a high resistance (open-circuit cell). If the battery has cell bypass circuitry, it will continue to function as an N-1 cell battery. If it has no cell bypass circuitry, the battery will fail by ceasing to deliver current. There is a leak size threshold of 1.0–2.5 μm, below which typical nickel-hydrogen cells take more than ten years to lose their water and fail by dry out. There is another leak size threshold at 3–4 μm where a cell will rapidly (in a few months or less) dry out if a leak larger than this threshold exists.

The possibility of leak latency is real for nickel-hydrogen cells, and can be caused by a number of mechanisms. Leak latency refers to the observation of no leak after a cell is manufactured and used for a period of time, and then the sudden observation of capacity or pressure loss due to leaking hydrogen. For the model discussed here, such leak latency could occur by two general mechanisms: (1) a pre-existing leak that was smaller than the detection limit of about 0.1 μm suddenly grew as a result of pressure or thermal stresses to be larger than 0.2 μm, allowing it to be readily detected, (2) a pre-existing leak that was larger than 0.2 μm but that was partially plugged with a solid material (making it subthreshold) suddenly was cleared to allow rapid loss of hydrogen. For either of these possibilities, it should be kept in mind that realistic leaks in nickel-hydrogen cell pressure vessels are more likely to look like thin cracks than tubular flow channels. For a crack, we can estimate the leak rate by using a tubular orifice with the same cross-sectional area. A pre-existing crack in a pressure vessel could grow as a result of stresses induced by pressure cycles or thermal cycling. In addition, it would not be surprising if such cracks were not partially filled with carbonates from reaction of the cell electrolyte with air, or with paint or other materials from the coatings applied to the external surfaces of the cell.

The key to leak latency found in this analysis is that it can readily result from the clearing or growth of a pre-existing leak path, and that pre-existing leak paths may not be easily detected if their gas flow path is less than 0.1–0,2 μm in size.

5. Conclusions

A model has been developed and used to analyze the loss of capacity and dry out of nickel-hydrogen cells as a result of pressure vessel leaks. This analysis has allowed a number of conclusions to be drawn about the behavior of nickel-hydrogen cells with leaks:

- Cells that are repeatedly cycled will not lose all capacity by leaking their hydrogen, but will fall to an intermediate but stable capacity where the loss of hydrogen is balanced by the loss of oxygen.

- There is a leak size threshold at 1–2.5 μm below which nickel-hydrogen cells will not dry out by gas leaking within a typical 10-year lifetime. There is another threshold at 3–4 μm above which a cell will rapidly fail open by dry out.

- There is a leak size threshold at 0.1–0.2 μm below which it will be difficult to identify the rate of capacity loss as differing significantly from normal wear-related capacity loss rates. There is another threshold at 0.3 μm above which cells will rapidly lose much of their capacity if not continuously cycled to generate additional hydrogen.

- Pre-existing leaks smaller than about 0.1 μm cannot be detected by the typical leak detection methods employed by cell manufacturers. Similarly, these leaks will not cause significant capacity loss during cell operational lifetimes if they do not grow.

- Leak latency can occur if pre-existing subthreshold leaks grow in size during the cell operation, or if a pre-existing leak path that is partially plugged (making it subthreshold) is cleared of the plug later in life.

LABORATORY OPERATIONS

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